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THE WATER SUPPLY OF MEMPHIS, TENNESSEE[1]

By J. N. Chester and D. E. Davis[2]

The water supply of Memphis, Tennessee, has been intermittently prominent in engineering discussions for forty years, because of the many unusual and interesting features connected with securing the water from the artesian sands. The artesian supply was first discovered in 1886 through the drilling of a well by a local industry. Shortly afterward the Water Company abandoned the plant on Wolf River, immediately above the city, which furnished untreated water, and in 1890 it put into operation the Auction Avenue artesian plant, which is still in service.

The City purchased the property of the Artesian Water Company in 1903 and shortly thereafter began to extend its search for water into other districts. In 1906 it erected a temporary air lift plant in South Memphis, some 5 miles distant, and in 1908 the Central Avenue air lift plant in the east end of the city and about 3½ miles from the Auction Avenue plant, was completed and is still in daily operation. Beginning in 1910 the Water Department supplemented its supply by sinking individual wells at points on the system where the pressure required reinforcing. These wells were equipped with vertical-shaft deep-well pumps actuated by electrical motors and delivered the water directly into the mains, thus incorporating both low-lift and booster service in the same unit.

At the present time, the plant supplies a population of about 180,000 which requires a little over 13,000,000 gallons of water daily, or 72 gallons per capita. One reason for this low per capita consumption is that about the same total quantity of water is taken from the water-bearing stratum by industrial and commercial plants. The combined fire and normal consumption demands upon the municipal works today call for a plant able to supply water at the rate of 32,000,000 gallons daily, whereas the existing facilities of the water department can furnish water at a rate of less than 24,000,000 gallons daily, the fluctuations in load being largely taken up by the individual motor-operated pumps scattered over the system. This situation led the water commissioners to retain the authors' firm to make an investigation of the conditions, and this paper will outline some of the interesting features of this unusual water works system which the investigation revealed.

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[1] Read before the Central States Section, September 28, 1920. Discussions are requested and should be sent to the Editor.

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Source of supply. All the water is obtained from an aquifer, or water-bearing stratum, of sand. This is reached at depths below the surface ranging from 340 to 575 feet and is overlaid and underlaid by clay strata. This artesian sand outcrops in a belt about 40 miles wide, lying parallel with the Mississippi and about 22 miles eastward from the city at its nearest point.

Quality of supply. The bacterial quality of the water is very good. Chemically, it is marked by considerable carbonic acid gas, which causes some red-water troubles. The solids in solution form soft scale, but there is no difficulty with hard scale. The character of underground waters from scattered wells is so likely to show marked variations that a chemical survey of the public and private wells throughout the city was made. As soon as a supply was taken from a well it was tested for free carbonic acid gas, and later duplicate samples were tested for iron and alkalinity. The results of this investigation showed that the water decreased in hardness as the distance eastward from the river increased. This steady decrease was not so marked in the case of the iron and carbon dioxide, but it held true in a general way. The iron content ranged from a trace to 3 p.p.m. The water obtained in the East End district is in every way better than the water nearer the river. This result, so far as carbon dioxide content is concerned, cannot be attributed to the air pumping in the East End because the electrically pumped wells display similar characteristics. Since there is a relationship between hardness of water and the distance of wells from the river, there might be a presumption that the river itself might be responsible for the result. This is quite improbable because the head under which the wells operate is greater than the elevation of the river, except, possibly, during the highest floods, thus preventing a backflow, and the river water is much softer than the ground water.

The artesian water contains from about 1.50 to 10 p.p.m. of dissolved oxygen, the quantity being higher in the supply pumped by the air lift than in the rest. Tap water from buildings with wrought iron or steel pipes was without any dissolved oxygen but the iron content was much higher, 14 to 20 p.p.m., than that in the water as it came from the wells, indicating the corrosive action of the carbon dioxide. This corrosive action has long been recognized in the city, so that the majority of premises have house plumbing and service lines entirely of lead. There was also a great increase in the alkalinity of the water before it was drawn from these taps. The water from many of the wells near the river gave off a distinct odor of hydrogen sulphide, but this was not detected in samples from wells in the eastern part of the city.

Future consumption. The future growth in the population of Memphis has been estimated by comparing its growth with that of a number of other cities with similar characteristics, from which it appears that an average growth of 5000 per year may be reasonably expected. Based upon a corresponding increased demand on the plant and taking into account the fire protection requirements as laid down by the National Board of Fire Underwriters, the average and maximum demands in gallons per day which the plant should be prepared to meet are,

	Average	*Maximum*
1920	13,200,000	31,800,000
1930	14,900,000	36,400,000
1940	20,000,000	46,000,000

Available supply. One of the critical questions in this study has to do with the decision as to whether or not it will be safe to further exploit this artesian supply, therefore, several methods of approach to the solution of the problem have been employed. The ultimate source of the ground water is, of course, that portion of the rainfall over the sand outcrop which finally percolates into the sand. The average annual rainfall where the artesian sand outcrops east of the city is about 48½ inches. An examination of the local conditions and records indicates that a conservative estimate of the proportion of the rainfall which percolates through the sand to Memphis is 15 per cent or 350,000 gallons per square mile of outcrop area, per day. As there are at least 320 square miles of this area which may safely be considered as the source of the supply for the city, it seems reasonable to count on an average daily available supply of over 100,000,000 gallons. This might be pictured as a slow-moving stream which would yield this amount without depleting the source.

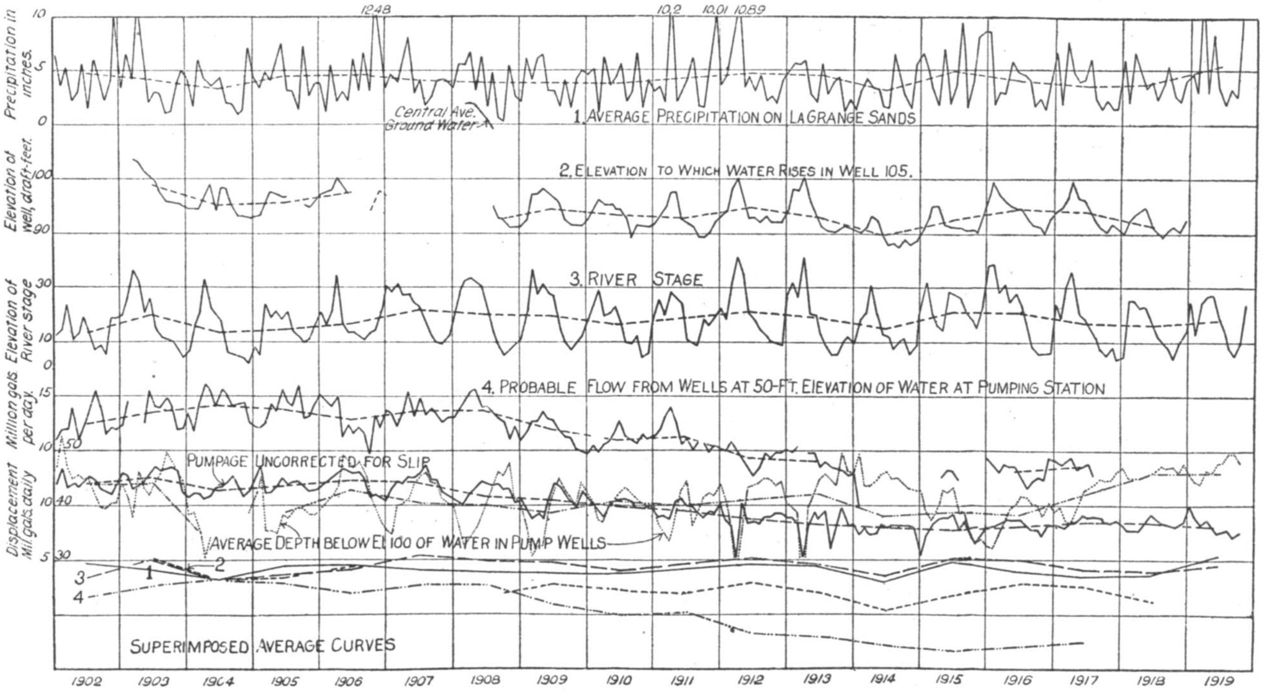

FIG. 1. MONTHLY AND YEARLY CURVES OF PRECIPITATION, RIVER STAGE AND WELL CONDITIONS

A second fruitful approach to the problem lies in the study of well records (some of which extend over a period of 30 years), to discover the effect of continuous draft on the water level of the artesian aquifer. The relationship between the rainfall, river level, and artesian water elevation together with other variables is shown in figure 1. These curves will be found of considerable interest and their study early developed the fact that comparisons of water elevations were of little value unless the seasonal variation in elevation was discounted. The variation between the high point in the spring to the low point in the fall has been as great as 11 feet, while the average annual variation appears to occupy a range of about 7 feet. There is also established a relationship between the elevation of the water in the river with the artesian water level, as well as between it and the rate of rainfall, which latter shows a lag in its effect upon the artesian plane, as might be expected.

No definite outlet can be established where the underground sands give up their water to the river, but the evidence leads to a strong presumption that some such connection actually exists. If this is so, then of course any rise in the river would tend to back up the water in the underground sands until a sufficient head was created as to force the underground water into the stream. This variation is of considerable significance in a practical way since, when coupled with the knowledge that the quantity of water derived from a well varies directly with the head on the well, this seasonal change affects to a marked degree the water which can be secured from the sands. The pumps at Auction Avenue are fixed as to elevation and the water cannot be drawn down in the pump well below a certain point. It is quite evident, then, that a 7 foot or greater difference in the head on the wells will make some difference in the quantity derived when the water in the well is lowered to the same elevation. A study of the relations between pumpage at Auction Avenue and the corresponding artesian water elevation during one period indicated that for an average difference of 9.4 feet in head on the wells there was a corresponding difference of 1,900,000 gallons per day as derived from the wells. At another period, for a head difference of 6 feet, the effect on the well delivery was 1,100,000 gallons per day. These results represent an average of 15 per cent of the available capacity at a given time.

The effect on the individual centrifugal pump wells cannot be studied in the same manner, but from the form of the characteristic and efficiency curves, it is known that a change in head does result in changed delivery conditions. In air-lift wells the effect of changed head on the wells is likewise marked, but since these changes do make a difference in the submergences of the wells and consequently the delivery under similar conditions of pumpage, it may be safely concluded that the quantity of water derived from these wells is also affected. A study of records from the air lift station at Central Avenue does, in fact, tend to substantiate the conclusions, for during one period when there was a variation of 11.6 feet observed in the head on the wells, there was a corresponding difference of approximately 500,000 gallons per day as derived from the wells during the two periods or about 12 per cent of the available water. For another period an observed drop in head of 4.1 feet resulted in a decrease of 270,000 gallons per day in the pumpage.

After sufficiently accounting for this seasonal effect of variations in artesian water level, the study of several sets of data seems to warrant the general conclusion that the drop in general water level from the time when the sands were first drawn upon to the present time is not in excess of 16 feet and probably not less than 5 feet. Stated in another way, the drop in water level per million gallons of water drawn from the sands by all wells (municipal and private) is probably not more than 0.3 foot, and considering the incomplete nature of the data involved, a working basis of 0.5 foot per million gallons will serve as an extremely conservative estimate, including something for a factor of safety.

Some further light on the available water supply results from the observation of the speed with which the water level in the wells resumes its initial undisturbed elevation after pumping has stopped. It is to be understood that when wells are pumped there is a drop in elevation of the water in and around the well and when pumping is stopped the water gradually approaches its former undisturbed level. It may be shown that the recovery at Auction Avenue was practically complete in five hours, of which 75 per cent was attained in one hour, while for the Central Avenue district, where the sand conditions are better, the corresponding figures are 1 hour and 20 minutes respectively. A well in the extreme south end of the city, which is affected by the pumping in the city and whose head was lowered 5 feet during the day, showed complete recovery during the night.

The study of all these data seems to warrant the conclusion that this artesian aquifer can be developed to at least three times its present yield before the economic limit of pumping is reached.

Life history of Memphis wells. One of the most interesting developments in connection with this whole investigation has been the derivation of the age characteristics and life history of the wells. Fortunately accurate monthly records of the flow of many of the wells have been available. Some of these records extend over a period of 30 years. In figure 2, the history of the yield of wells in the Auction Avenue District, drilled in different years, is shown graphically. Each curve represents the mathematical average yield of a group of wells drilled during a given year. In order to determine the ageing of the wells, each series has been plotted by showing the yield for each year of its age, plotted on the same base. The resulting average curve is quite instructive and indicates that there is a very definite limit to the life of every well drilled in this locality. The yield of every well drops off rapidly during the first five years of its history and more gradually during its later life, this in spite of the fact that the wells are given periodic attention in the way of flushing and cleaning, the results of which are reflected in the curves. The data from which these curves were drawn were taken from the meter records of each well, as measured and recorded monthly, since 1902, by the resident engineer, and are believed to accurately represent true conditions obtaining over the period.

The life history of the Central Avenue wells is of the same general character (see figure 3), although their initial yields, and consequently their yield on each succeeding year, is much higher than the average in the other district, and the ageing effect similar. The similar ageing of the wells leads naturally to a discussion of the causes for this decrease in yield in these wells, and the explanation lies at hand that the clogging of the strainers by the fine sand, by corrosion and incrustation, and by the deposit of iron oxide and possibly other solids, notably lignite, are some of the contributing factors leading towards this result. There are also indications that the sand in the vicinity of the strainers becomes permeated with accumulated material, such as finer sand and principally iron oxide or ferric hydroxide, so that ultimately the opportunity for ingress of artesian water into the wells becomes exceedingly limited. This is recognized as a practical consideration, since the Water Department has maintained a well crew for the purpose of periodically cleaning these wells

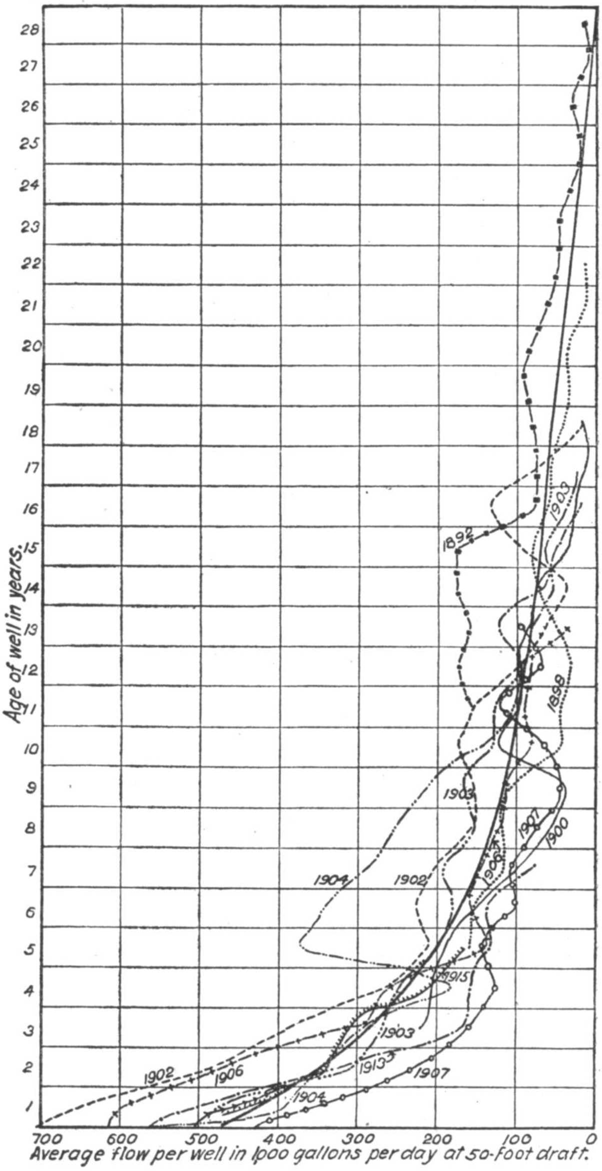

Fig. 2. Average Life of Wells in Auction Avenue District

by different methods of washing, viz., removing the strainer, cleaning it, and restoring it into the well; and telescoping a worn-out well by sinking a pipe of smaller diameter within the original casing to a point below the original level and placing another strainer at this new sand stratum.

The effectiveness of various methods employed in improving the flow from wells which have fallen off in yield may be seen by consulting table 1, made up to show the average increase per well as derived from a series of observations extending over a period of years. It is quite evident then that in order to maintain the supply at a uniform rate, it becomes necessary to drill a certain number of wells each year. It is estimated that in order to maintain the Auction Avenue yield at 10,000,000 gallons per day, it is necessary to drill five new wells per year.

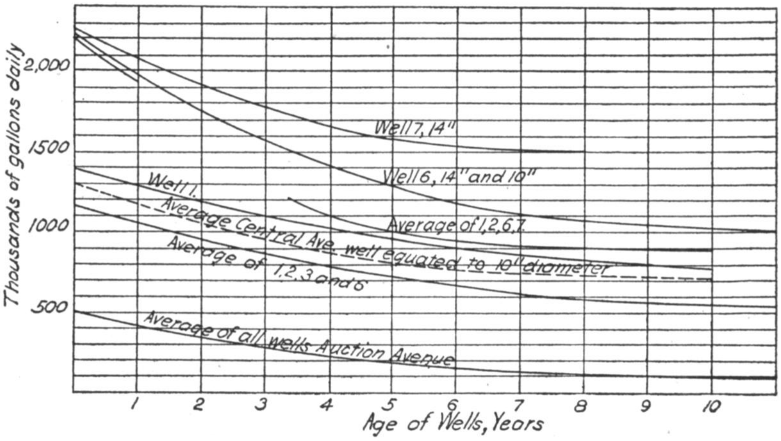

FIG. 3. LIFE AND YIELD OF WELLS FROM TEST DATA

In order to compare the yields of wells in the two districts, the conditions were reduced to a similar base and all wells compared on a 10-inch diameter. The resulting curves are shown in figure 4, where the calculated yields for 10-inch wells are shown and the observed yields of 12- and 14-inch wells. In searching for the reason for the marked difference in well yields in the two districts, the influence of well diameters, strainer lengths, and sand analyses were studied. Fortunately samples of sand from many of the wells had been saved and rather definite conclusions as to its effect are therefore warranted. To summarize the whole subject of well yields, the following conclusions are set down in brief form:

TABLE 1

Average increase in flow of wells after cleaning in various ways

YEAR OF DRILLING	OPEN FLUSH			TOOL FLUSH			OVERHAUL			TELESCOPE		
	Before*	Increase	Per cent	Before*	Increase	Per cent	Before*	Increase	Per cent	Before*	Increase	Per cent
1892	78,161	68,000	87.0	113,000	76,000	69	79,000	94,000	117	93,000	344,000	370
1898	140,000	21,000	15.0	104,000	106,000	102	67,000	134,000	200	35,000	253,000	720
1900	117,143	41,000	35.0	107,000	115,000	108	65,000	132,000	203	88,000	361,000	410
1902	147,000	25,000	17.0	140,000	69,000	49	80,000	154,000	193	102,000	150,000	150
1903	200,000	22,000	11.0	122,000	65,000	53	119,000	162,000	135	41,000	540,000	1300
1904	180,000	9,000	5.0	132,000	121,000	92	133,000	165,000	124			
1906	126,000	34,000	27.0	143,000	122,000	85	106,000	188,000	177	68,000	327,000	480
1907	103,400	60,000	58.0	111,000	110,000	100	148,000	130,000	88	49,700	318,000	640
1913				105,000	105,000							
Total....	1,091,704	280,000		1,077,000	784,000		797,000	1,159,000		476,700	2,293,000	
Average.	136,463	35,000	25.6	119,666	87,111	72.8	99,625	145,000	145	68,100	328,000	482

* Flow in gallons per day before renewing well.

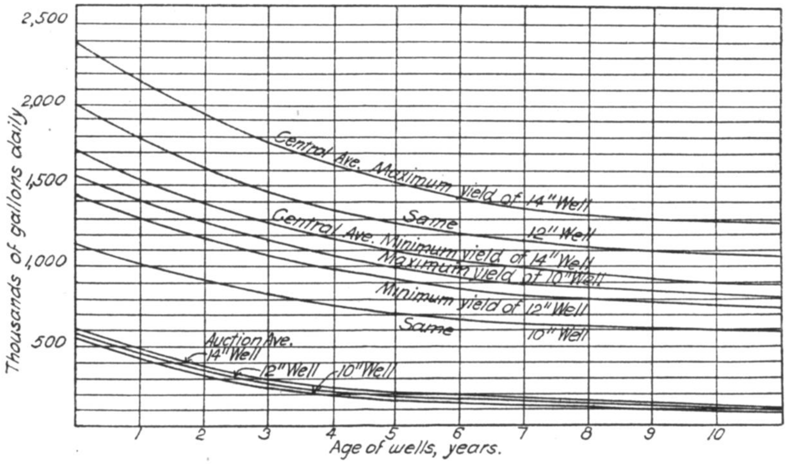

FIG. 4. EXPECTED LIFE AND YIELD OF WELLS

Expected yields are based on a 40-foot drop between the ground water elevation some distance from the well and the elevation of water in the well. The yields given above are 45 per cent of the yield of a well when pumped alone, or an allowance of 55 per cent for interference.

1. That all wells drilled into this sand drop off in yield with advance in years according to a rather definite law.

2. That there is a very rapid drop off in yield in the Auction Avenue wells within the first two years and that the rate of decrease in yield after that date is more gradual.

3. That for the average well at Auction Avenue, the initial yield when first drilled is about 570,000 gallons per day, which decreases to approximately 100,000 gallons per day at the end of ten years, corresponding to yields of 1,300,000 and 700,000 respectively for similar wells at Central Avenue under this same consideration.

4. That the wells at Central Avenue show from two times (for 10-inch wells) to four times (for 14-inch wells) greater yield than do wells in the Auction Avenue District.

5. That the probable explanations for the decreasing yield of wells are:

a. The clogging of the strainers by fine sand.

b. The corrosion and incrustation of the strainer.

c. The deposit of iron oxide and possibly other solids, notably lignite, in the strainer openings and in the surrounding sand.

6. That in order to maintain a supply at a constant level, it becomes necessary to sink new wells periodically.

7. That an increase in the diameter of a well affects the yield according to strainer and casing friction.

8. That the effective size of the sand has a very appreciable effect on the yield, that is, the larger the sand, the greater the yield, and that yields vary as the square of the ratios of the effective sizes of sand.

9. That the effective size of sands in the East End District is much greater than in the Auction Avenue District.

10. That two or three times as much water may be anticipated under the same conditions from the East End as from Auction Avenue for a 10-inch well; two and one-half to three and one-half times for 12-inch; and three to four times for 14-inch, consequently the East End District offers much better opportunities for exploitation than the Auction Avenue District.

Attention is especially directed to statements (7) and (8) as indicating the paramount importance of the size of sand grain upon the yield of the wells, also as showing that in wells of large yield, where friction loss is a factor, the wells of large diameter are a good investment when measured in terms of yield.

Interference of wells. There was an opportunity at the Central Avenue Station to make a detailed study of the mutual interference of the wells and the effect of their spacing upon this interference. The capacity of each when the others were shut down was first determined. Then these wells were pumped in pairs and the mutual interference of each well in a pair was found to result in a loss of capacity per well ranging from 3 per cent in one pair to 25 per cent in another. The wells were next pumped in various groups of three, when the interference was found to reduce the capacity per well from 14 to 26 per cent. Finally, the wells were pumped in groups of four, and the loss of capacity per well under such operating conditions was 28 to 34 per cent. These data are only applicable to the local conditions at this station at the time of the tests. For instance, the minimum loss of 3 per cent mentioned above was due largely to the fact that one of the wells was new and of large capacity.

The effect of the spacing on the interference is well shown by the complete data, but the details need not be given here except for one example to show the close agreement of theory with observed results. This is the case of three wells. No. 7 is at one end of the base of a triangle, the base being 515 feet long. It yields 1,700,000 gallons daily when the other wells are not pumped. No. 8 is at the other end of this base and yields 2,060,000 gallons when it alone is pumped. No. 1, is at the apex of the triangle, 350 feet from No. 7 and 225 feet from No. 8. When well 8 is pumped and the others are not pumped, the water table at that well drops to 11.1 feet below its normal elevation, and the water table at well 7 is pulled down 2.65 feet. When only well 7 is pumped, the water table there is pulled down 8.7 feet and at well 8 it drops 2.1 feet. Since the yield of these wells has been found to vary directly with the drop in the water table, after allowing for friction losses, the theoretical yields are easily computed. When well 7 alone is pumped, it causes a drop in the artesian water table at well 8, so that at the latter the available head to cause water to percolate into that well is only 11.1–2.1 or 9 feet. When both wells are pumped simultaneously, the yield of well 8 will be reduced from the yield when it alone is pumped by an amount proportional to the reduced head. The theoretical yield will therefore be 9/11.1 × 2,060,000 gallons, or 1,670,000 gallons. In the same way the theoretical yield of well 7, with both wells 7 and 8 pumped, can be found to be 1,180,000 gallons. Under such conditions the two wells will theoretically yield 2,850,000 gallons; the field tests gave a combined yield of the two under such conditions of 2,950,000 gallons. The effect of pumping at these two wells on well 1 was carefully checked by observing the drop in the artesian water table there, and the theoretically determined elevations agreed within a few inches with the observed elevations. The rise in the head may be conceived as being uniform in all directions when a single well is being pumped, giving the appearance, therefore, of an inverted cone to the artesian water head curve. When more than one well is operating these cones intersect, thereby cutting off the flow available to each. The interference becomes more pronounced, the more wells there may be located in a given vicinity. The interference would probably be lessened where the wells are placed in a single line. The theoretical relationship between rise in elevation with distances from the well for a 12-inch well flowing 2,000,000 gallons and with friction and other loss of 4 feet shows that the interference will be roughly as given in Table 2.

TABLE 2

Effect of spacing of wells at Central Avenue on their mutual interference when pumped in pairs

Distance between wells in feet	10	50	100	200	300	500	1,000	3,000	4,000
Percentage of interference	67	48	41	32	29	23	18	6	0

In determining the best spacing of wells, other factors than their interference must be considered, such as the cost of connecting them with the water mains, the cost of equipping them with pumping apparatus, and the cost of pumping, including the effect of friction losses on that cost.

Auction Avenue pumping station. This station was built in 1890 and its present condition, after thirty years' service, offers an opportunity for an interesting study of the depreciation and obsolescence of a high-grade plant of the date of its construction. The buildings are in excellent condition, and the same is true of the two 135 by 5½-foot stacks. The latter are amply able to furnish draft for any requirements which are likely to arise here; each stack has a capacity of 750 horse power under the operating conditions that are probable.

After thirty years' service the six Heine water-tube boilers set in two batteries are still in use, which speaks well for the care given to them. They furnish steam at very low pressure, 100 pounds being their rated maximum, and they are small according to present practice and without superheaters and other features now considered desirable in stations of this general character. Tests of three of them gave an evaporation of 7.59 pounds of water per pound of coal, from and at 210°, into steam at 85.6 pounds pressure. These are good results for the coal and such boilers. The criticism of the plant is that it is obsolete to a considerable degree.

The three vertical, compound, high-duty Worthington pumps were erected in 1899 and their steam ends entirely renewed about ten years ago. They are set in a dry well, 38 feet in diameter and 47½ feet deep. They are in good general condition, but their slip was found to be 15.7, 17.4 and 23.4 per cent, the smallest slip being in a pump in which new plungers were fitted in 1919. Their test duty when erected was over 105,000,000 foot-pounds per 100 pounds of coal, whereas the plant has averaged only 27,500,000 to 40,200,000 foot-pounds since 1908. This low duty is due to a number of conditions, such as inability to operate any unit at its full capcity for more than a short period, the condition of the auxiliaries, and the necessity of keeping ready for fire service over 100 per cent of the capacity needed for normal service. The operating requirements make it difficult to keep the pumps in the best running condition. The auxiliary equipment should be replaced in large part.

TABLE 3

Operating cost comparisons showing average annual costs and costs per million gallons pumped from January 1, 1914, to January 1, 1919

	AUCTION AVENUE		CENTRAL AVENUE		SEGREGATED WELLS		AVERAGE	
	Average annual	Per million gallons	Average annual	Per million gallons	Average annual	Per million gallons	Average annual	Per million gallons
Salaries	$14,048	$5.52	$11,754	$12.18	$2,610	$5.65	$28,412	$7.16
Fuel	18,532	7.28	19,373	20.08	19,527	42.30	57,432	14.48
Oil and waste	2,140	0.84	1,341	1.91				
Repairs to plant	3,376	1.32	1,314	1.36	} 1,214	2.63	10,618	2.68
Miscellaneous	66	0.03	667	0.69				
Total	$38,162	$14.99	$34,949	$36.22	$23,351	$50.58	$96,462	$24.32
Well maintenance	8,411	3.31	120†	0.12	300†	0.65	8,831	2.22
Tunnels, etc. maintenance	807	0.32					807	0.32
Total	$47,380	$18.62	$35,069	$36.34	$23,651	$51.23	$106,100	$26.76
Pumps, special maintenance*	3,742	1.47					3,742	1.47
Wells, special maintenance	28,809	11.31	600†	0.62			29,409	7.41
Total	$79,931	$31.40	$35,669	$36.96	$23,651	$51.23	$139,251	$35.11
Interest, (calculated)	34,000	13.36	7,040	7.31	4,600	9.98	45,640	11.50
Depreciation, (calculated)	12,750	5.01	4,400	4.56	2,300	4.99	19,450	4.90
Total	$126,681	$49.77	$47,109	$48.83	$30,551	$66.20	$204,341	$51.51
Gallons per day (corrected)	6,980,000		2,642,000		1,262,000		10,884,000	

* Proportion of whole amount.

† Estimate.

Auction Avenue well system. The method of developing the ground water supply at Auction Avenue has long been a subject of unusual engineering interest, and the condition of the wells and collecting system today deserves rather detailed description, for there is little printed information concerning it. When the station was built, it will be recalled, the present methods of obtaining water from large wells were either unknown or not of demonstrated reliability. Hence only the artesian head of the water in the aquifer was utilized to deliver the supply to the pumping station.

From the bottom of the dry well at the pumping station a shaft 10 feet in diameter was sunk to a depth of 80 feet below the surface. The shaft was sealed at the top and around the pump suction mains where they enter it. At the bottom, the shaft has been connected with a brick-lined tunnel, which has been extended from year to year until it is now somewhat over a mile long. From this tunnel numerous timber-lined drifts have been driven, having a total length of over five miles. Access to the tunnel and drifts is had through a number of shafts. The drifts run to or by the wells, which are connected to them in such a way that the well water flows freely into them. There are 70 of these wells in service now, most of them 10 inches in diameter.

On two occasions this supply has been seriously polluted. In 1912, a flood caused by high water in the Mississippi broke into one of the shafts, which is believed to have been damaged previously, at the time some pavements were laid. In 1919, a sewer settlement, due to some unknown cause, resulted in the flow of sewage down the outside of a well casing and through the timber lining of a drift into the artesian water. Deplorable consequences attended this last case of contamination.

These major cases of pollution and several minor cases led the author to make a critical examination of the relative locations of wells and sewers and it was found that there were 44 wells within 10 feet of sewers, measured horizontally. He has accordingly advised encasing the sewer with reinforced concrete or replacing it with cast iron pipe for a distance on each side of the well. This recommendation is based not only on the inherent possibility of leakage from the average sewer, but also on the conditions caused by the sinking of some of the wells. The loosening of the earth about the well casing, particularly when the well is sunk rapidly, may afford such an opportunity for very free percolation of water and even for the running of fine sand containing much water in its pores, that the earth supporting a neighboring sewer may be disturbed in the course of time, causing the sewer to crack and leak. There have been 23 instances of surface subsidence caused by the washing of materials into drifts, due to a breaking of the connection between a well and drift. This breaking can be attributed only to the loosening of the material about the well casing to such a degree that the resulting pressure of the material above the connection finally becomes great enough to cause its failure.

The condition under which the Auction Avenue Station's supply is obtained, the great difficulty of shutting off one or more drifts from the tunnel in case polluted water is flowing through them, and the present condition of the tunnel and drifts, coupled with the fact that wells in this part of the city yield much less water than those farther east, determined the author to advise discontinuing further extensions of this plant. It is his opinion that all wells at this location should be discontinued as soon as an adequate supply can be obtained elsewhere.

Central Avenue pumping station. This station was built in 1907–1908, apparently without much expectation that it would become a permanent plant. The engine room was well laid out, but the boiler room is so cramped that there is insufficient room to tend fires, handle coal and ashes, and renew boiler tubes.

Steam is furnished by five 5 by 18-foot return tubular boilers rated at 150 horse power each, but unable to meet this rating because each has only a 60 by 2½-foot steel guyed stack to furnish draft, which such a stack cannot supply properly. Tests of three boilers showed thay were evaporating 6.93 pounds of water, from and at 210°, into steam at 113.2 pounds pressure, per 100 pounds of coal. There are adequate facilities for coal storage, but the conditions make the handling of coal and ashes very expensive.

The six wells directly connected to this station are pumped by air lift. The station has five cross-compound,condensing, two stage compressors, each rated at 500 cubic feet of free air per minute at its maximum permissible speed of 120 r.p.m. All of them exhaust into a surface condenser with 1000 square feet of cooling surface, the condensing water coming from and returning to the receiving basin into which the well water is discharged. The compressors and condenser are in fair condition, and two of the compressers gave a duty when tested by the author in pumping a large yield well of 22,500,000 foot-pounds per 1000 pounds of steam.

The high service pumping is done by five compound condensing simplex pumps. Each is rated at 1,000,000 gallons and has a separate surface condenser, which may, however, be connected to any or all pumps. On test, three of these pumps showed a duty of 26,400,000 foot-pounds per 1000 pounds of steam.

The average annual duty of the whole station during the last ten years has been from 10,300,000 to 13,200,000 foot-pounds per 100 pounds of coal.

Central Avenue wells. It has already been stated that the relatively coarse sand of the artesian stratum near this station yields freely a water which contains less iron and carbonic acid gas, is lower in alkalinity and causes less clogging of the strainers and the sand about them than the water at the Auction Avenue station. When the station was built, the choice of the air lift for pumping the wells was a wise one. Three 10-inch wells yield from 800,000 to 900,000 gallons each when the artesian water table is lowered 17 feet and another such well, 2200 feet from the station, yields 1,000,000 gallons when the water table is drawn down 35 feet. There is a 14-inch well which gives 1,600,000 gallons with a lowering of 18 feet in the water table, and a 12-inch well yielding 2,060,000 gallons with 16 feet lowering of the water table. The decrease in yield of the wells with their age has already been mentioned. The water is delivered into a well-built covered receiving basin 32 feet in diameter and about 25 feet deep.

Independent well pumps. For many years the use of independent or segregated pumps at Memphis has been of special interest to water works engineers. As long ago as 1903, the late T. T. Johnston, consulting engineer of the water department, was interested in developing such pumps and a considerable investment was made in them under his direction down to 1908. In the following year a type of pump devised by W. J. Wills, then general superintendent of the department, was developed and its installation in some of the wells was begun in 1910. At present there are 14 of these pumps installed. They have an electrically driven vertical shaft with a screw pump at its bottom, which lifts water to the suction of a centrifugal pump having its runner at the top of the same vertical shaft.

Tests of three of these equipments showed an efficiency of 30.6 to 43.5 per cent. The bottom pump has a much lower efficiency than the centrifugal pump at the top, and where this bottom pump has much work to do, the efficiency of the complete unit is less than the efficiency when the bottom pump carries a smaller proportion of the total load.

In a general way, the author's investigations at Memphis convince him that the work done with independent pumps there has made a substantial contribution to deep well pumping practice, and that there will be a field in that city for independent well pumps until marked additions are made to the art of deep well pumping as now conducted. Certain rules should be observed in installing such units, however, in order to take full advantage of all the experience gained with them down to date.

The wells should not be sunk on streets or alleys where the presence of sewers introduces dangerous conditions and it is necessary to place the pumps in pits difficult to drain and affording little space for maintenance and repairs. The pumps should be above ground, in a building of good appearance, with a roof, part of which can be removed to enable the shaft to be lifted out be means of a derrick and tackle. Each pump should have an air separator and an automatic recording Venturi meter on its discharge pipe, with gate and check valves. There should be a recording watt-hour meter in each pump house, so that records of the input and output of the pump will give immediate warning of any falling off of efficiency.

Expenses. Memphis has had a sufficiently long experience with each of its three methods of deep-well pumping to permit comparisons of cost to be made between the systems over a period of years and under the conditions of operating there existing. The figures in table 3 those taken from the operating records of the Water Department, which is operated as a self supporting concern and practically as though it were a private company. In explanation of the term "special maintenance," it will be recalled that in order to maintain the supply of water from the wells intact, it becomes necessary to drill new wells at regular intervals. The cost of such items of renewal are charged to this special account. The cost of overhauling and rebuilding pumps was spread over several years, as it appeared unfair to penalize any one year with this expenditure. The fixed charges are not the actual amounts paid, but are based on certain percentages applying upon the investment in the plant as carried on the books of the Water Department.

Improvements. The purpose of this paper is to report the condition of the Memphis works, as the author found them. These works have been discussed a great deal in engineering circles, but comparatively little has been published concerning them of late years, and very little has been ever printed concerning them considering the interest they aroused for something like twenty years. From what has been said, it is readily seen that parts of the plant are outgrown and parts present objectionable features in the light of our present knowledge of public sanitation, and in closing the author will indicate briefly his recommendations for their improvement. The greatest need is storage of water, to equalize the work of the low-service pumps and give an opportunity to rid the water of its iron and dissolved gases, as well as to afford a suitable place for chlorination. Attempts to chlorinate the water at the Auction Avenue station have not been satisfactory because of operating conditions. It is possible to build a 10,000,000 gallon reservoir near that station which will accomplish the purposes named, and in addition furnish an adequate storage supply for fire protection near the part of the city where the need for it is greatest.

The Auction Avenue station is a well built structure and located so favorably for serving some of the most important parts of the city that the heavy investment there should be utilized so far as practicable and economical. Fortunately this can be done by remodeling the plant and developing gradually a new system of wells free from the objections to those now in use. So far as these new wells are concerned, they can be sunk on a line connecting this station with the Central Avenue station and thus be able to supply either station, and the two stations can be so equipped that there will be duplicate apparatus for pumping the wells, installed at different points, however, which is highly desirable. Not the least among the advantages to be secured through extending the line towards the East End district is the opportunity it affords of reaching the coarser sand and better water of that district.

The low-service pumping capacity at the Auction Avenue station can be improved and increased by converting one of the Worthington pumps into a triple-expansion engine by replacing its steam end. This can be used in delivering water from the present collecting tunnel to the new storage reservoir. The other Worthington pumps can be kept as they are for service in the present fashion, so long as the collecting tunnel is used. Two 10,000,000-gallon pumps should be installed for direct pumping from the storage reservoir into the distribution system and a modern boiler plant is a necessity.

The Central Avenue station, located at a point where the city owns a large plot of land, should have a 5,000,000-gallon storage reservoir. In order to place this station on a good operating basis, there should be installed three batteries of water tube boilers with superheaters, a new stack, a 5,000,000-gallon high-duty pump, a new Corliss air compressor and coal handling equipment. The extension of the well system supplying this station can be readily carried on as needed.

The independent wells, discharging into the distribution mains, can apparently be pumped most advantageously by electrically driven segregated pumps, generally speaking, but wells located along the collecting mains discharging by gravity to the pumping stations can apparently be pumped most advantageously by the air lift. These are general statements based on local Memphis conditions, and the author makes them with the distinct reservation that even at Memphis the best equipment of each well should be considered as an independent engineering problem.

Like most distribution systems, that at Memphis needs extensions and reinforcement at places. The meters need overhauling and more attention should be given to waste prevention and the continuous supervision of the quality of the water.